Computers in Industry 95 (2018) 38–53

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

3D printing of functional anatomical insoles

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ARTICLE INFO

Article history:
Received 17 February 2017
Received in revised form 27 November 2017
Accepted 1 December 2017
Available online xxx

Keywords:
Anatomical insoles
Customisation
Additive manufacturing
Functionalisation

ABSTRACT

Anatomical insoles and additions have a corrective action on the footwear user. They are intended to reduce and adequately distribute plantar pressure among support points, thus minimising the stress these points can undergo. Such customised components have traditionally been manufactured either handcrafted or by subtractive techniques, i.e. by milling a sheet of material. Latest advances in additive manufacturing (AM) techniques and, in particular, the popularisation of 3D printing by fused deposition modelling (FDM), have opened new ways for the production of anatomical insoles. These technologies allow additional functionalities to be added, as for instance the use of materials with antimicrobial properties, or, at a structural level, zonal control in 3D design to increase cushioning capacity. The latter cannot be achieved by traditional manufacturing techniques, in that the inside of the element is not accessible. However, there are no CAD tools available for the design and production of insoles, which are specifically oriented to take advantage of the benefits that AM can bring about. Based on a previous study about the possibilities for functionalisation of anatomical insole materials and structures, this paper intends to review certain CAD methodologies for the design and manufacture of insoles by means of additive manufacturing techniques. These techniques will be employed to design and produce prototypes through which it is possible to assess such techniques. In order to study the feasibility of using this technology for the manufacture of customised insoles in a real production environment, this paper presents a comparative analysis of the proposed technology and the technology that is currently being used.

1. Introduction

In the field of footwear, the insole (see Fig. 1) is a component located between the foot and the shoe sole. Being in direct contact with the foot [1], the insole supports body weight. Therefore, it directly affects the biomechanics of the foot and the body as a whole [2]. An anatomical insole should be intended to reduce and adequately distribute plantar pressure among support points, thus minimising the stress these points can undergo during the execution of physical activity or while standing for long periods. This element changes the way the foot hit the ground, distributing the loads from the zones that support higher pressure among the areas that supports a lower one. Fig. 2 shows an example of the pressure areas of a given foot. In this case, it is observed that the plantar pressure is concentrated in the heel, the metatarsal, and to a lesser extent, in the toe. Incorrect support may lead to injuries in the long term [3]. There are certain essential aspects characterising an insole. Firstly, its morphology, in that it has to be adapted to the anatomy of the foot sole, which is characterised by three main arches. These arches shall be adequately balanced to achieve perfect support. Secondly, the density of the material(s) chosen for production, which directly redounds to certain properties, like flexibility, hardness, resistance, shock absorption, etc. There are also other corrective elements, called additions (see Fig. 3), which are added on the metatarsal area of the insole in order to dampen impacts while walking and retain the foot in an anatomically correct position. This results in an increase of the contact area of the foot and therefore, the pressure is distributed in a larger area rather than being concentrated in a located point.to unload the areas that bear the highest pressure.

Anatomical insoles are mainly addressed to people with foot arch unbalances. Insoles help to achieve perfect support of the foot while walking and standing. is provoked by the weakening of ligaments supporting the plantar fascia, and is the cause of biomechanical disorders, such as pes planus and pes cavus. Pes

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https://doi.org/10.1016/j.compind.2017.12.001
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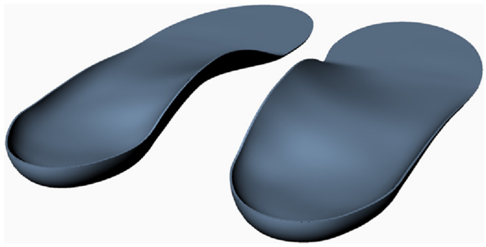

Fig. 1. Anatomic insole.

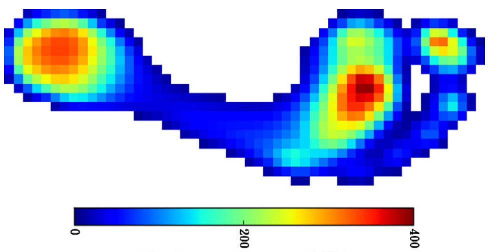

Fig. 2. Pressure points foot map.

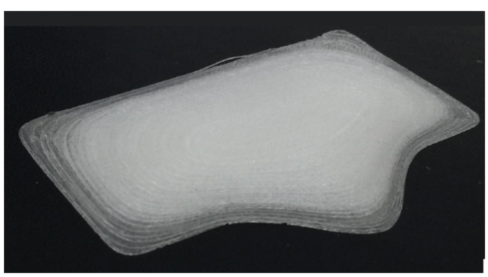

Fig. 3. Insole addition.

planus is characterised by the fact that plantar arches are partially or completely fallen. According to Cacace et al. [4], pes planus is estimated to affect approximately 3–25% of the adult population globally. Although in most cases this condition does not cause any pain, people suffering this problem have a higher odds of developing changes in bone structures in the long term, such as Hallux Valgus or bunion and Hallux Rigidus (osteoarthritis of the big toe joint). Pes cavus is a type of foot with an excess arch in the plantar fascia, i.e. in pes cavus the contact surface in the midfoot and toe areas of the foot sole are reduced and consequently pressure on the rest of the foot areas resting on the ground increases. According to [5], although this condition affects a smaller population percentage than pes planus (10–15%), 60% of these are likely to suffer pain and associated pathologies, including calluses, changes in bone structures, limited joint mobility, and arterial disease. This fact becomes even more significant when wearers suffer from certain illnesses, such as diabetes, where correct pressure distribution is critical to prevent ulceration [6].

In recent years, the production of anatomical insoles for a given user was carried out by subtractive manufacturing (SM) techniques. This is a process by which objects are constructed by successively cutting material away from a solid block of material using a CNC machine. With regard to the production of anatomical insoles, subtractive manufacturing poses certain drawbacks [7]. First of all, material waste upon cutting material away from the original block. Secondly, lack of flexibility to alternate materials in different areas according to the user's needs, since the material to be used is pre-determined by the original block. Thirdly, it is impossible to gain access to the inside of the insole. Nevertheless, the recent advances in additive manufacturing allow the limitations inherent to SM to be overcome.

Additive manufacturing (AM) is a process by which a three-dimensional object is built up by superimposing material layers using different manufacturing techniques. Although additive manufacturing dates back to 1987, it has gained momentum over recent years thanks to the advances in technology and cost reduction, which allows very complex objects to be manufactured in short time and at a competitive cost. There are different additive manufacturing techniques such as material extrusion, in which a nozzle moving over a plane melts a plastic filament; material jetting, in which droplets of build material are selectively deposited; or powder bed fusion, in which thermal energy selectively fuses regions of a powder bed [8]. As far as anatomical insole production is concerned, this paper focuses on additive manufacturing by material extrusion, which will be referred to as FDM (Fused deposition modelling) 3D printing in this paper. This term is more commonly accepted and used, even though it is the name given by the company Stratasys to this technology.

The reasons for choosing FDM printing is the low cost of the equipment, which makes it suitable for use by the light industry, as is the case of the footwear sector, and the fact that 3D printing systems can add different polymeric materials to the object to be produced.

The use of FDM 3D printing for the manufacture of anatomical insoles also brings about new production possibilities which would otherwise not be feasible by traditional methods. Among these, the possibility to add new properties to the insole stands out; this way, new specific functionalities are conferred on the insole, which provide added value. This is called *functionalisation*. On the one hand, it is possible to functionalise the material by adding an extra component that provides new features. For instance, it is possible to create a filament to be extruded that incorporates an antimicrobial compound to prevent the onset of infections [9]. On the other hand, manufacturing by FDM allows the functionalisation of the geometric structure of insoles by incorporating internal elements by zones. Such elements are to modify the intrinsic properties of the material employed as well as the external geometry of the insole. For example, hollow areas can be defined in the insole design, which will modify the insole functionality in terms of shock absorption, flexibility, etc.

Therefore, additive manufacturing alleviates many of the constraints derived from the use of the *Design for Manufacturing* (DFM) paradigm [10]. Under this paradigm, the designer is to create the design always taking into account the limitations established by the manufacturing system. Although there is significant improvement with respect to traditional manufacturing, none of the 3D printing systems is completely free from limitations. This becomes evident in the above-described example on the production of anatomical insoles with functionalised structure by FDM. In this case, the main software applications for printing, pose the drawback of managing the insole geometry as a water-tight object and ignore any structure contained therein, in such a way that the insole is manufactured as a completely solid object. It is therefore necessary to create a specific CAD tool for insoles that makes it possible to provide the 3D model with the relevant properties that allow precise manufacture by FDM. This paper intends to propose several CAD methodologies aimed at the design and production of insoles by additive manufacturing, more specifically, the design of internal structures that can alter the shock absorption capacity in different areas, and the processing of